

COURSE OBJECTIVES

CHAPTER 7

7. RESISTANCE AND POWERING OF SHIPS

1. Be able to define effective horsepower (EHP) physically and mathematically.
2. Be able to state the relative between velocity with total resistance and velocity with effective horsepower.
3. Be able to write an equation for total hull resistance as a sum of viscous resistance, wave making resistance and correlation resistance. Be able to physically explain each of these resistive terms.
4. Be able to draw and explain the flow of water around a moving ship showing laminar flow region, turbulent flow region, and separated flow region.
5. Be able to draw the transverse and longitudinal wave patterns when a displacement ship moves through the water.
6. Be able to define the Reynolds number with a mathematical formula. Be able to explain each parameter in the Reynolds equation with units.
7. Be qualitatively familiar with the following minor sources of ship resistance:
 - a. Steering Resistance
 - b. Air and Wind Resistance
 - c. Added Resistance due to Waves
 - d. Increased Resistance in Shallow Water
8. Read and interpret a ship resistance curve including humps and hollows.
9. Be able to state the importance of naval architecture modeling of the resistance on the ship's hull.
10. Be able to define geometric and dynamic similarity.
11. Be able to write the relationships for geometric scale factor in terms of length ratios, speed ratios, wetted surface area ratios or volume ratios.
12. Be able to describe the law of comparison (Froude's law of corresponding speeds) physically and mathematically and state its importance in model testing
13. Qualitatively describe the effects of length and bulbous bows on ship resistance.

14. Be familiar with the momentum theory of propeller action and how it can be used to describe how a propeller creates thrust.
15. Define Coefficient of Thrust and Thrust Loading.
16. Know the relationship between thrust loading and propeller efficiency.
17. Define the following terms associated with the screw propeller:
 - a. Diameter
 - b. Pitch
 - c. Fixed Pitch
 - d. Controllable Pitch
 - e. Reversible Pitch
 - f. Right Handed Screw
 - g. Left Handed Screw
 - h. Pressure Face
 - i. Suction Face
 - j. Leading Edge
 - k. Trailing Edge
18. Be familiar with cavitation including the following:
 - a. The relationship between thrust loading and cavitation.
 - b. The typical blade locations where cavitation occurs.
 - c. Spot Cavitation.
 - d. Sheet Cavitation.
 - e. Blade Tip Cavitation.
 - f. Operator action to avoid cavitation.
 - g. The effect of depth on cavitation.

Chapter 7: Resistance and Powering of Ships

7.1 Introduction

One of the most important considerations for a naval architect is the powering requirement for a ship. Once the hull form has been decided upon, it is necessary to determine the amount of engine power that will enable the ship to meet its operational requirements. Knowing the power required to propel a ship enables the naval architect to select a propulsion plant, determine the amount of fuel storage required, and refine the ship's center of gravity estimate.

Throughout history, naval architects have endeavored to increase the speed of ships. Increased speed would enable a warship to close with its opponent, or conversely, to escape from an attack. Increased speed enables merchant vessels to reach port sooner and maximize profit for its owner.

Until the early 1800's, wind was the force used to propel ships through the water and ships could only go as fast as the wind would propel them. Additionally, because ships were constructed of wood, the structural limitations of wooden hull configurations drove hull designs to primarily meet the structural needs while hydrodynamics was only a secondary concern. With the advent of steam propulsion in the early 1800's, naval architects realized that ship speeds were no longer constrained by the wind and research began into the power required to propel a hull through the water using this new propulsion medium.

Testing of full-scale ships and models determined that the power required to propel a ship through the water was directly related to the amount of resistance a hull experiences when moving through the water.

The development of iron hull construction produced radical changes in hull strength and hull design. Gone were the blunt bows and full hull forms of early sailing vessels. Capitalizing on the added strength of iron hulls, naval architects could design ships with finer bows and as a result, ship speeds increased.

About the time of the Civil War, the modern screw propeller was developed, replacing the paddle wheel as the prime mode of ship propulsion. The screw propeller, with many modifications to its original design, remains the principle method of ship propulsion to this day.

This chapter will investigate the differing forms of hull resistance, ship power transmission, and the screw propeller. Additionally, we will investigate ship modeling and how full-scale ship resistance and performance can be predicted using models in a towing tank.

7.2 The Ship Drive Train

Before ship resistance and powering can be examined in any detail, the process for transmitting engine power into the water needs to be examined. Figure 7.1 shows a simplified picture of a ship's drive train.

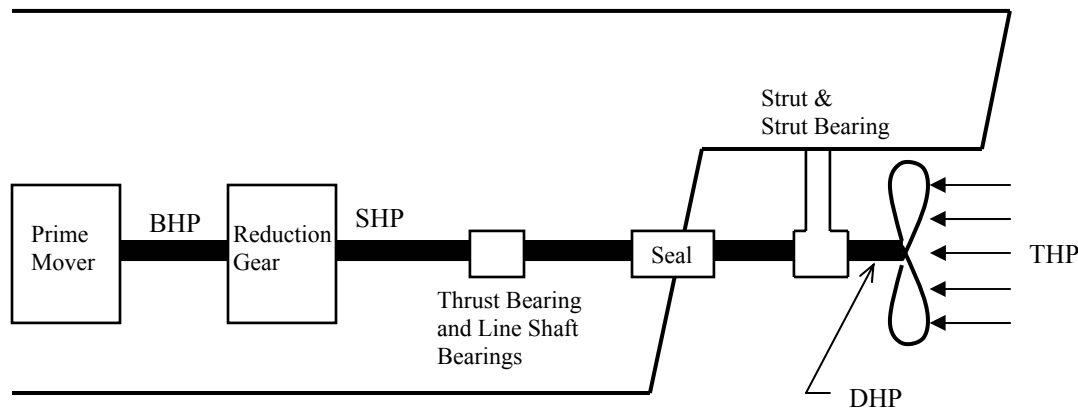


Figure 7.1 – Simplified ship drive train

7.2.1 Brake Horsepower (BHP)

Brake horsepower (BHP) is the power produced by the ship's prime mover. The prime mover is the portion of the drive train that converts heat energy into rotational energy. For most ships, the prime mover is a steam turbine, gas turbine, or diesel engine. For some ships, the prime mover can be a large electric motor (electric drive). The output speed of the prime mover is usually quite high (several thousand rpm for a gas turbine at full power) and must be reduced to a usable rotational speed.

7.2.2 Shaft Horsepower (SHP)

Shaft horsepower (SHP) is the power output the reduction gears (if installed). Reduction gears are necessary to reduce the high revolutions per minute (rpm) of the prime mover to a much slower shaft rotation speed required for efficient screw propeller operation. For example, a steam turbine at full power may operate at 5,700 rpm and the reduction gear will reduce that to 258 shaft rpm. In order to accomplish the speed reduction between the prime mover and propeller shaft, and to produce the torque necessary to spin the propeller, a reduction gear is usually quite large and heavy. Reduction gears are very efficient at power transmission, with only a one or two percent loss of power between input (BHP) and output (SHP). The relationship between BHP and SHP is called the *gear efficiency* (η_{gear}), and is written as follows:

$$\eta_{gear} = \frac{SHP}{BHP}$$

Note: SHP is always less than BHP

7.2.3 Delivered Horsepower (DHP)

Delivered Horsepower (DHP) is the power delivered by the shaft to the propeller. The amount of power delivered to the propeller will be less than shaft horsepower because of transmission losses in the shaft. Losses are usually quite small: 2-3%. These losses occur in the bearings, stern tube and its seal, and strut bearings. The thrust bearing takes the axial propeller thrust produced by the rotation of the propeller shaft and transmits the linear force of the thrust to the ship, which in turn produces translational motion of the ship. Line shaft bearings are used to support the weight of the propeller shaft between the reduction gear and stern tube. The stern tube and seal are necessary to keep the ocean out of the ship. Transmission losses are primarily due to friction and can be felt as heat in the bearings. The difference between delivered horsepower and shaft horsepower is referred to as *shaft transmission efficiency* (η_{shaft}), and is defined as:

$$\eta_{shaft} = \frac{DHP}{SHP}$$

7.2.4 Thrust Horsepower (THP)

Thrust Horsepower (THP) is the power produced by the propeller's thrust. THP is smaller than DHP due to inefficiencies inherent in converting the rotational motion of the propeller into linear thrust. The propeller is the least efficient component of the ship's drive train. Delivered and thrust horsepower are related through a quantity called the *propeller efficiency*. Typically, a well-designed propeller will have an efficiency of 70-75% at the ship's design speed.

7.3 Effective Horsepower (EHP)

Up to this point, each of the powers (BHP, SHP, and DHP) can be physically measured someplace in the ship. However, these powers are of no use in the initial design stages of a ship's hull. Shaft horsepower and brake horsepower are quantities that are purchased from the engine manufacturer. Likewise, the amount of thrust a propeller can produce is a product of analysis and calculation. However, the naval architect must still determine the amount of power (BHP or SHP) actually required to propel the ship through the water. The amount of power is determined through the concept of *Effective Horsepower* (EHP). Effective horsepower is defined as:

“The horsepower required to move the ship's hull at a given speed in the absence of propeller action.”

Effective horsepower is determined through model data obtained from towing tank experimentation. In these experiments, a hull model is towed through the water at a given speed while measuring the amount of force resisting the hull's movement through the water. Model resistance data can then be scaled up to full-scale ship resistance. Knowing a ship's total hull resistance and its speed through the water, the ship's effective horsepower can be determined using the following equation:

$$EHP = \frac{R_T V}{550 \frac{ft-lb}{sec-HP}}$$

where: EHP is the effective horsepower (HP)

R_T is the total hull resistance (lb)

V_S is the ship's speed (ft/sec)

Model testing is carried out over the expected speed range of the ship with resistance data collected at each testing speed. Effective horsepower is then calculated and plotted as shown in Figure 7.2. The reason behind the shape of the curve will be covered later.

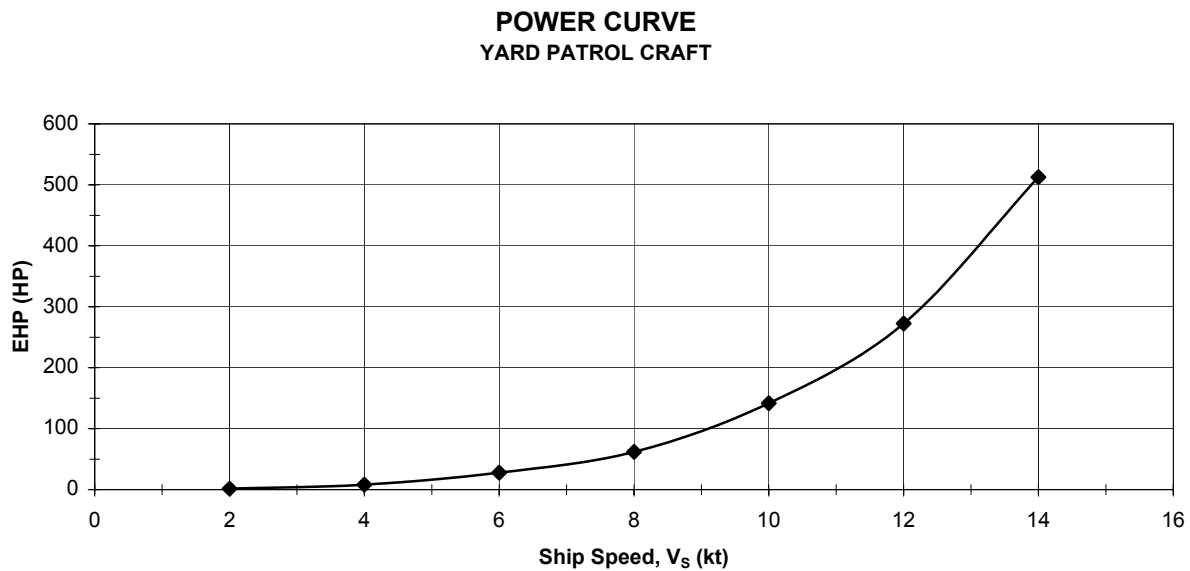


Figure 7.2 – Curve of effective horsepower for a Navy YP

7.3.1 Hull Efficiency

Once the ship's effective horsepower has been determined, it is now necessary to relate EHP to the power produced by the drive train. This is done by relating the power required to tow the ship through the water (EHP) to the power produced by the propeller (THP). The ratio of effective horsepower to thrust horsepower is called the *hull efficiency* (η_H), and is defined as:

$$\eta_H = \frac{EHP}{THP}$$

7.4 Propulsive Efficiency

Having established that the link between the power required to tow a ship through the water (EHP) and the power produced by the propeller (THP) is the hull efficiency, it is now possible to determine the shaft or brake horsepower the ship will need. Figure 7.3 shows a block diagram of the various components of a ship's drive train and the powers associated with each component that can aid in the determination of the required SHP or BHP.



Figure 7.3 – Block diagram of a ship's drive train

Instead of having to deduce the effect of all the separate efficiencies of each component in the drive train, the separate efficiencies are often combined into a single efficiency called the *propulsive efficiency* (η_p) or propulsive coefficient (PC).

$$\eta_p = PC = \frac{EHP}{SHP}$$

The propulsive efficiency is the ratio of effective horsepower to shaft horsepower, therefore allowing the designer to make a direct determination of the shaft horsepower required to be installed in the ship. Common values of propulsive efficiency typically range from 55% to 75%.

Example 7.1 Model testing has determined that a ship has an EHP of 30,000 HP at a speed of 19 knots. Assuming a propulsive efficiency of 70%, what SHP is required to be installed to achieve 19 knots?

$$\eta_p = \frac{EHP}{SHP}$$

$$SHP = \frac{EHP}{\eta_p} = \frac{30,000HP}{0.70}$$

$$SHP = 42,860HP$$

A total of 42,860 horsepower (43,000 HP) should be installed to achieve a speed of 19 knots.

Once a value of shaft horsepower has been determined, various combinations of prime movers can be considered based on power produced, weight, fuel consumption, etc for installation in the ship.

7.5 Total Hull Resistance (R_T)

As a ship moves through calm water, the ship experiences a force acting opposite to its direction of motion. This force is the water's resistance to the motion of the ship, which is referred to as "total hull resistance" (R_T). It is this resistance force that is used to calculate a ship's effective horsepower. A ship's calm water resistance is a function of many factors, including ship speed, hull form (draft, beam, length, wetted surface area), and water temperature.

Total hull resistance increases as speed increases as shown below in Figure 7.4. Note that the resistance curve is not linear. In fact, resistance is proportional to velocity to the n^{th} power, where " n " varies from a value of 2 at low speeds and increases to a value of approximately 5 at high speeds. In later sections of this chapter we will investigate why resistance increases so rapidly at high speeds. Also shown in Figure 7.4 is a bump, or "hump", in the total resistance curve. This hump is not a mistake, but a phenomenon common to nearly all ship resistance curves that will be discussed later.

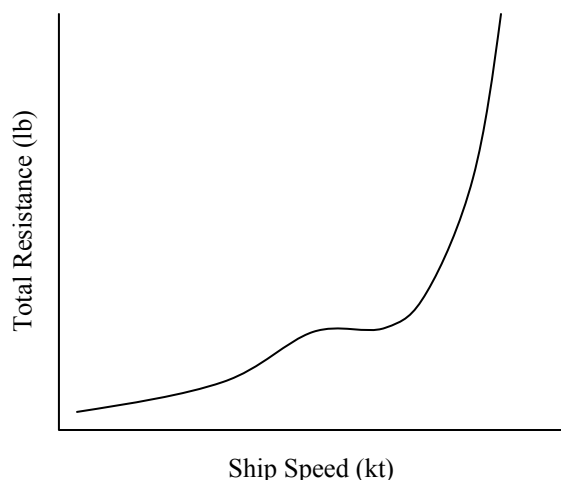


Figure 7.4 – Typical curve of total hull resistance

As shown in previous sections, the power required to propel a ship through the water is the product of total hull resistance and ship speed. Therefore the horsepower required can be proportional up to ship speed raised to the 6th power!

For the ship operator planning a voyage, getting from Point A to Point B in a shortest amount of time (high speed) requires a lot more power than traveling the same distance at a slower speed. This increase in power is felt directly in the amount of fuel burned during the transit. A ship's fuel consumption curve is similar in shape to its horsepower and total resistance curves. Voyage planning requires careful attention to transit speed and fuel consumption rates to ensure that the ship arrives at its destination with an adequate supply of fuel onboard. The U.S. Navy generally requires that ships arrive with no less than 50 percent fuel onboard as a reserve.

7.6 Components of Total Hull Resistance

As a ship moves through calm water, there are many factors that combine to form the total resistance force acting on the hull. The principle factors affecting ship resistance are the friction and viscous effects of water acting on the hull, the energy required to create and maintain the ship's characteristic bow and stern waves, and the resistance that air provides to ship motion. In mathematical terms, total resistance can be written as:

$$R_T = R_V + R_W + R_{AA}$$

Where:

- R_T = total hull resistance
- R_V = viscous (friction) resistance
- R_W = wave making resistance
- R_{AA} = resistance caused by calm air

Other factors affecting total hull resistance will also be presented. Figure 7.5 shows how the magnitude of each component of resistance varies with ship speed. At low speeds viscous resistance dominates, and at high speeds the total resistance curve turns upward dramatically as wave making resistance begins to dominate.

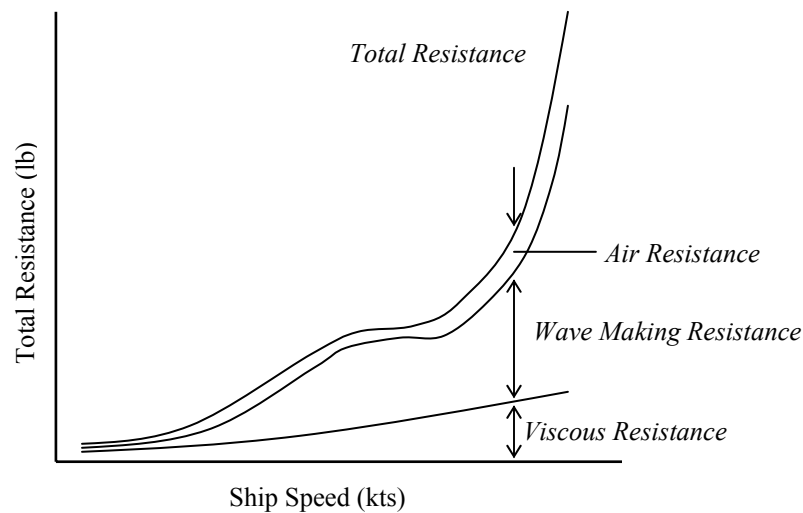


Figure 7.5 – Components of Hull Resistance

7.6.1 Dimensionless Coefficients

Naval architects, as well as all engineers and scientists, use dimensionless coefficients to describe the performance of a system or to compare different systems to each other. Automotive engineers use a “drag coefficient” to describe the performance of a car. Aviators use the “Mach number” to compare the speed of an aircraft to the speed of sound. Naval architects use many dimensionless coefficients to describe the design and performance of a ship’s hull. Dimensionless coefficients allow the naval architect to compare model test data to full-scale ship data, or to compare the performance of several ship types.

The field of ship resistance and propulsion makes extensive use of standard dimensionless coefficients. The derivation of these standard coefficients is accomplished through dimensional analysis. Dimensional analysis is beyond the scope of this text, however, you can learn about dimensional analysis from any text on fluid mechanics or from Volume 2 of “Principles of Naval Architecture” published by the Society of Naval Architects and Marine Engineers.

7.6.1.1 Dimensionless Resistance and Velocity

Just as total hull resistance is the sum of viscous, wave making, and air resistance, we can write an equation for total resistance in terms of dimensionless coefficients.

$$C_T = C_V + C_W$$

Where: C_T = coefficient of total hull resistance
 C_V = coefficient of viscous resistance
 C_W = coefficient of wave making resistance

Note that air resistance is not represented in dimensionless form. This is because the dimensionless form of resistance is a product of model testing, and most models do not have superstructures. Model tests are usually used to determine the performance of the hull and do not include the superstructure.

Since total hull resistance is a function of hull form, ship speed, and water properties, the coefficient of total hull resistance is also a function of hull form, ship speed, and water properties. The coefficient of total hull resistance is found from the following equation:

$$C_T = \frac{R_T}{\frac{1}{2} \rho V^2 S}$$

Where: R_T = total hull resistance (lb)
 ρ = water density (lb-s²/ft⁴)
 V = velocity (ft/s)
 S = wetted surface area of the underwater hull (ft²)

Naval architects also use a dimensionless form of velocity called the “*Froude number*” (F_n), named in honor of William Froude (1810-1878), one of the pioneers in ship model testing.

$$F_n = \frac{V}{\sqrt{gL}}$$

where: V = velocity (ft/s)
 g = acceleration of gravity (ft/s²)
 L = length of ship or model (ft)

Another common, although not dimensionless, way of expressing velocity is through the *speed-to-length* ratio. This ratio is similar to the Froude number except that the gravity term is omitted.

$$\text{speed-to-length ratio} = \frac{V}{\sqrt{L}}$$

Many times the velocity term in the above ratio is expressed in knots (1 knot = 1.688 ft/s). Care should be taken when using this ratio to ensure what units of the velocity term are correct. An example of using dimensionless coefficients to present data is shown in Figure 7.6, a plot comparing C_T and ship speed. The significance of this plot will be discussed in later sections of this chapter.

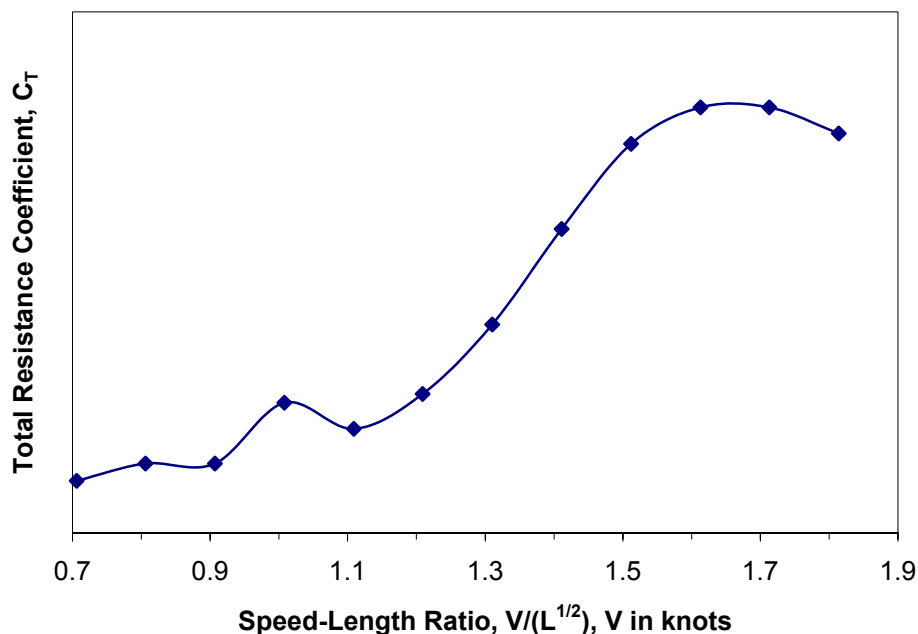


Figure 7.6 – Typical relationship between C_T and speed to length ratio.

7.6.2 Viscous Resistance (R_v)

As a ship moves through the water, the friction of the water acting over the entire wetted surface of the hull causes a net force opposing the ship's motion. This frictional resistance is a function of the hull's wetted surface area, surface roughness, and water viscosity. Viscosity is a temperature dependent property of a fluid that describes its resistance to flow. Syrup is said to be a very viscous liquid; the fluid particles in syrup being very resistant to flow between adjacent particles and to other bodies. On the other hand, alcohol has a low viscosity with little interaction between particles.

Although water has low viscosity, water produces a significant friction force opposing ship motion. Experimental data have shown that water friction can account for up to 85% of a hull's total resistance at low speed ($F_n \leq 0.12$ or speed-to-length ratio less than 0.4 if ship speed is expressed in knots), and 40-50% of resistance for some ships at higher speeds.

Naval architects refer to the viscous effects of water flowing along a hull as the hull's frictional resistance. Frictional resistance is only one part of viscous resistance, however. Viscous resistance also includes the effects of pressure distribution around the hull as well as additional resistance caused by the formation of eddies along the hull.

The flow of fluid around a body can be divided into two general types of flow: laminar flow and turbulent flow. A typical flow pattern around a ship's hull showing laminar and turbulent flow is shown in Figure 7.7

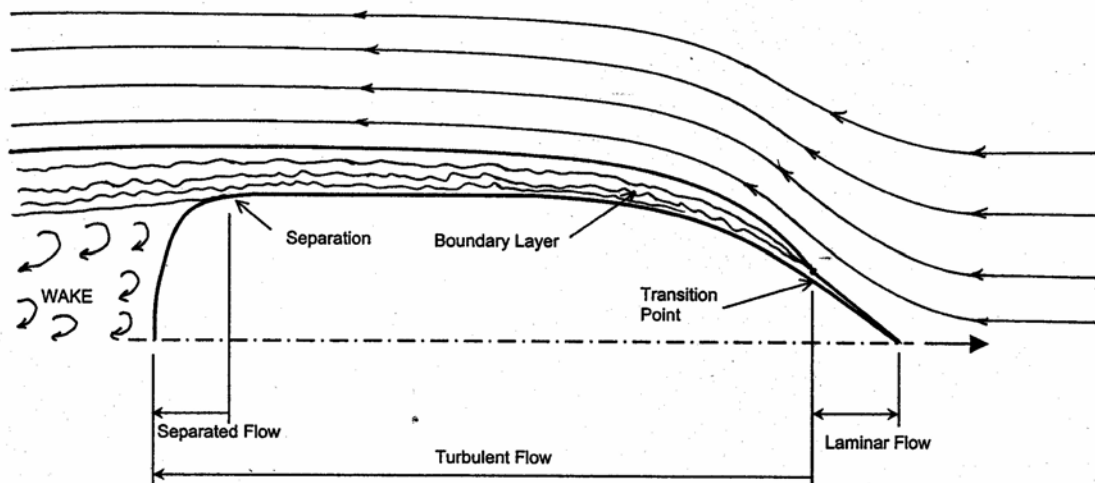


Figure 7.7 – Typical water flow pattern around a ship's hull

Laminar flow is characterized by fluid flowing along smooth lines in an orderly fashion with a minimal amount of frictional resistance. For a typical ship, laminar flow exists for only a very small distance along the hull. As water flows along the hull, the laminar flow begins to break down and become chaotic and well mixed. This chaotic behavior is referred to as turbulent flow and the transition from laminar to turbulent flow occurs at the transition point shown in Figure 7.7.

Turbulent flow is characterized by the development of a layer of water along the hull moving with the ship along its direction of travel. This layer of water is referred to as the “boundary layer.” Water molecules closest to the ship are carried along with the ship at the ship’s velocity. Moving away from the hull, the velocity of water particles in the boundary layer becomes less, until at the outer edge of the boundary layer velocity is nearly that of the surrounding ocean. Formation of the boundary layer begins at the transition point and the thickness of the boundary layer increases along the length of the hull as the flow becomes more and more turbulent. For a ship underway, the boundary layer can be seen as the frothy white band of water next to the hull. Careful observation of this band will reveal the turbulent nature of the boundary layer, and perhaps you can see some of the water actually moving with the ship. As ship speed increases, the thickness of the boundary layer will increase, and the transition point between laminar and turbulent flow moves closer to the bow, thereby causing an increase in frictional resistance as speed increases.

Mathematically, laminar and turbulent flow can be described using the dimensionless coefficient known as the Reynolds Number in honor of Sir Osborne Reynolds’ (1883) contribution to the study of hydrodynamics. For a ship, the Reynolds Number is calculated using the equation below:

$$R_n = \frac{LV}{\nu}$$

Where: R_n is the Reynolds number
 L = length (ft)
 V = velocity (ft/sec)
 ν = kinematic viscosity of water (ft²/sec)

For external flow over flat plates (or ship hulls), typical Reynolds number magnitudes are as follows:

Laminar flow: $R_n < 5 \times 10^5$
Turbulent flow: $R_n > 1 \times 10^6$

Values of R_n between these numbers represent transition from laminar to turbulent flow.

Example 7.2 A ship 250 feet in length is traveling at 15 knots in salt water at 59°F ($\nu = 1.2791 \times 10^{-5} \text{ ft}^2/\text{sec}$). Calculate the ship's Reynolds number at this speed.

$$R_n = \frac{LV}{\nu} = \frac{(250 \text{ ft})(15 \text{ kt}) \left(1.688 \frac{\text{ft}}{\text{s} - \text{kt}} \right)}{1.2791 \times 10^{-5} \frac{\text{ft}^2}{\text{s}}}$$

$$R_n = 4.949 \times 10^8 \quad \text{water flow around the ship is definitely turbulent}$$

Example 7.3 A model 5 feet in length is being towed at a speed of 5 ft/sec in fresh water at 59°F ($\nu = 1.092 \times 10^{-5} \text{ ft}^2/\text{s}$). Calculate the model's Reynolds number.

$$R_n = \frac{LV}{\nu} = \frac{(5 \text{ ft}) \left(5 \frac{\text{ft}}{\text{s}} \right)}{1.092 \times 10^{-5} \frac{\text{ft}^2}{\text{s}}}$$

$$R_n = 2.29 \times 10^6 \quad \text{the model is also operating in the turbulent regime}$$

Note: Ships have turbulent flow over nearly their entire length except when operating a very low speed, although even at low speeds laminar flow is present for only one or two feet.

7.6.2.1 Separation Resistance

Figure 7.7 shows that at some point along the hull, the boundary layer separates from the hull. Flow separation usually occurs near the stern where the hull's curvature is too great for the boundary layer to remain attached to the hull. The space between the smooth flowing water and the hull is filled with eddies as shown in Figure 7.7. This region of eddies is known as the ship's wake, and due to viscous effects, the wake is pulled along with the ship, thus increasing the ship's resistance. The resistance due to flow separation from the hull is sometimes referred to as "separation resistance". The flow separation point is a function of hull design and ship speed. A hull that has smooth lines into the stern will have a separation point that is farther aft and tends to have a narrower wake with less separation resistance than a hull that has discontinuities that cause the flow to become separated from the hull. For naval vessels with transom sterns, the separation point is at the stern.

7.6.2.2 Viscous Pressure Drag

The previous sections discussed viscous resistance as being a type of friction, a force acting tangent to the hull. Another form of viscous resistance is related to the pressure distribution normal to the hull. Figure 7.8 shows a body submerged in an ideal (inviscid) fluid. As the fluid

flows around the body, there is a pressure distribution normal to the body. In the forward section of the hull there is a component of pressure resisting motion, and in the aft section of the body there is a component of pressure assisting motion. In an ideal fluid these pressure forces are equal and the body experiences no resistance.

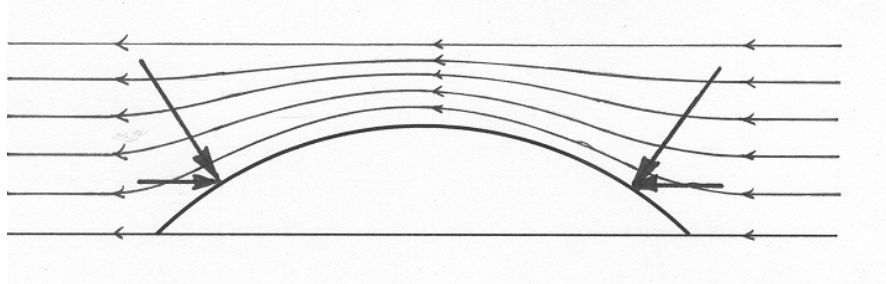


Figure 7.8 – Ideal flow around a submerged body

However, water is not an ideal fluid, and therefore some differences in the flow around a body exist. Figure 7.9 shows a hull submerged in water. Note how the turbulent boundary layer has developed along the hull producing a wake similar to that shown in Figure 7.7. In the forward portion of the hull pressure forces act normal to the surface; however, in the aft portion of the hull the boundary layer reduces the forward acting component of pressure. This reduction in the forward acting component results in a net resistance force due to pressure acting on the hull. This increase in resistance due to pressure is called “viscous pressure drag” or “form drag”, and is sometimes also referred to as the normal component of viscous resistance.

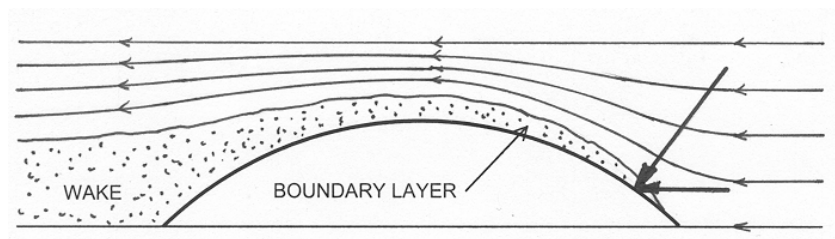


Figure 7.9 – Flow around a body submerged in water

As you might expect, from looking at Figure 7.9, the shape of a ship's hull can influence the magnitude of viscous pressure drag. As you may expect, ships that are short in length with wide beams (a low length to beam ratio) will have greater form drag than those with a larger length to beam ratio. Also, ships that are fuller near the bow (e.g. bulk oil tanker) will have greater form drag than ships with fine bows (e.g. destroyer).

7.6.2.3 Coefficient of Viscous Resistance (C_V)

The dimensionless form of viscous resistance is the coefficient of viscous resistance (C_V). This coefficient is a function of the same properties that influence viscous resistance itself: hull form, speed, and water properties. The equations for the coefficient of viscous resistance that follow are empirical products of many years of towing tank testing, and are internationally recognized by the International Towing Tank Conference (ITTC). The coefficient of viscous resistance takes into account the friction of the water on the ship as well as the influence of hull form on viscous pressure drag.

$$C_V = C_F + KC_F$$

where: C_V = coefficient of viscous resistance

C_F = tangential (skin friction) component of viscous resistance

KC_F = normal (viscous pressure drag) component of viscous resistance

The skin friction coefficient (equation below) is based on the assumption that the hull is a flat plate moving through the water, and is a function of Reynolds number (ship speed, length, and water properties). The form factor (K) accounts for the effect of hull form on viscous resistance.

$$C_F = \frac{0.075}{[(\log_{10} R_n) - 2]^2}, \quad R_n = \frac{LV}{\nu}$$

$$K = 19 \left(\frac{\nabla}{LBT} \times \frac{B}{L} \right)^2$$

7.6.2.4 Reducing the Coefficient of Viscous Resistance

Note from the above equations that for a given speed, as ship length increases the skin friction (tangential) component of viscous resistance decreases. Note also that as the displaced volume of a ship decreases (length, beam, and draft remain constant), or if the ship's beam decreases the normal or pressure drag component of viscous resistance decreases. Therefore the ideal hull design, from a viscous resistance standpoint, is to have a hull that is very long, very narrow, with little submerged volume. However, this type of hull is not very practical from the standpoint of stability or cargo carrying capacity. Therefore, the naval architect must make some tradeoffs in the design process.

7.6.3 Wave Making Resistance (R_w)

The second major component of hull resistance is the resistance due to wave making. As a ship moves through the water it creates waves. These waves are produced at the bow and stern and propagate outwards from the ship. A ship moving through the water creates two types of wave patterns. They are the divergent and transverse wave systems illustrated below in Figure 7.10. This figure is reproduced from “Introduction to Naval Architecture” by Gillmer and Johnson.

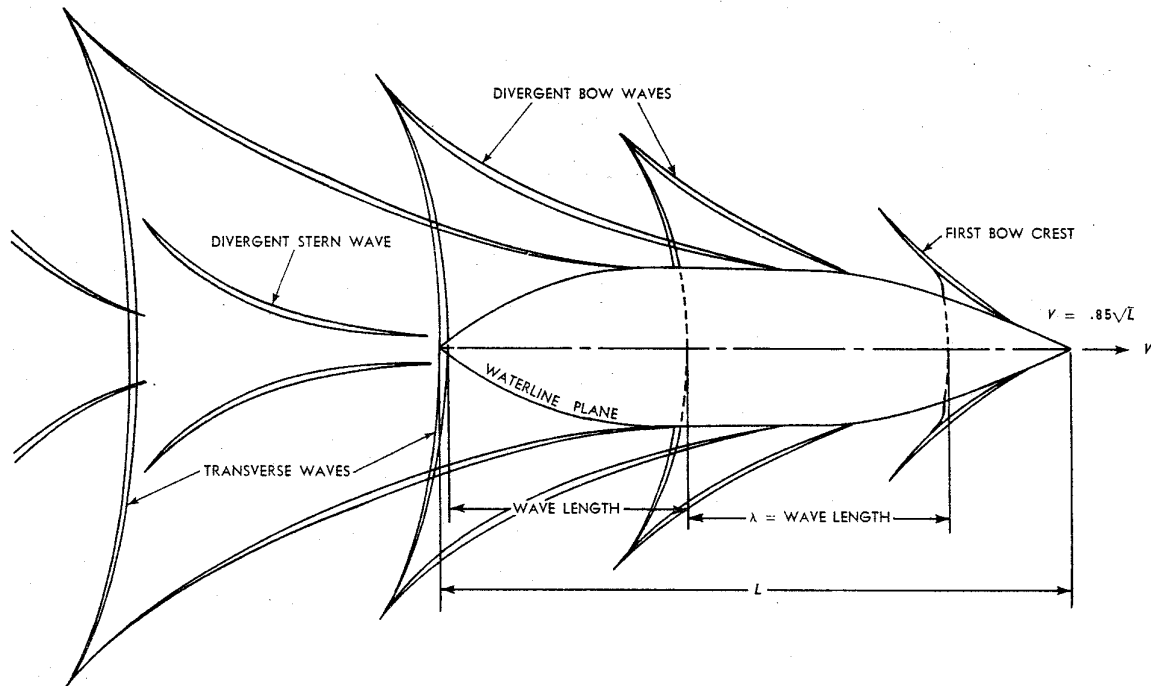


Figure 7.10 – The divergent and transverse wave patterns generated by a ship

Sir William Froude (1810-1878) did much of the early research in wave making resistance and his results and conclusions in this field are used to this day. Figure 7.11 is Froude's 1877 sketch of the wave patterns produced by a ship (from “Principles of Naval Architecture, Volume 2” published by the Society of Naval Architects and Marine Engineers). Compare Froude's sketch to the photographs of actual ships in Figures 7.12 and 7.13 and note the similarities. The transverse wave system holds particular importance with respect to wave making resistance. The transverse wave travels at approximately the same speed as the ship as the ship is producing this wave. At slow speeds the transverse waves have short wave length and several crests can be seen along the ship's length as shown in Figure 7.13. The relationship between wave length and resistance will be explored later in this section.

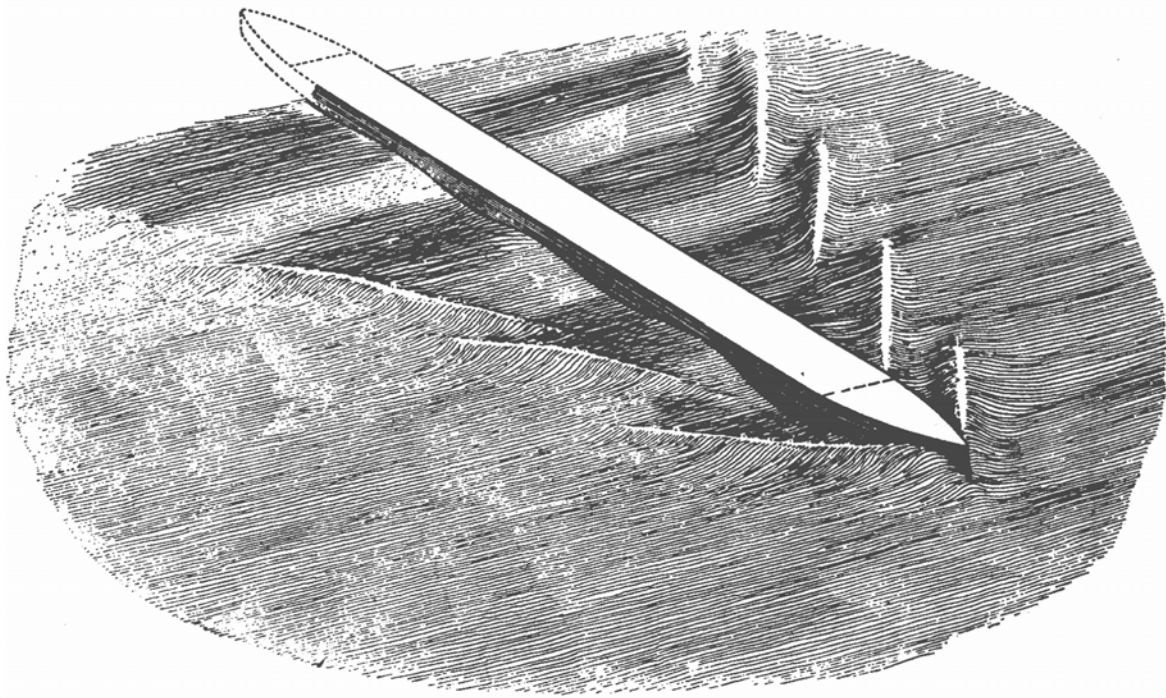


Figure 7.11 – Froude's sketch of a characteristic wave train for ships.



Figure 7.12 - USNS SPICA (left) conducting vertical replenishment with another ship. Note the divergent wave patterns emanating from SPICA. (U.S. Navy photo)



Figure 7.13 – Transverse wave pattern along the hull of a replenishment ship (U.S. Navy photo)

The creation of waves requires energy. As ship speed increases, the height of the waves produced by the ship increases and therefore the energy required to produce these waves also increases. Any energy expended by the ship to create and maintain these waves represents energy that could have been used to make the ship go faster through the water. This lost energy is referred to as wave making resistance and becomes a limiting factor in the speed of a ship.

As previously mentioned, a ship moving through the water creates waves at the bow and stern. As ship speed increases not only does the height of the waves created by the ship increase, but the length of the waves also increases. Wave theory states that the energy in a wave is proportional to the square of the wave height. At some speeds, the crests and troughs of the bow and stern waves will reinforce each other producing higher overall wave heights and a subsequent increase in resistance. This mutual interference between waves and increased resistance produces the characteristic hump in the ship's resistance curve as shown in Figure 7.14. At other speeds the bow and stern waves tend to interfere each other, producing lower overall wave heights and a subsequent decrease in resistance. This decrease in resistance produces the hollows in the ships resistance curve. Since the energy in a wave depends on the square of the wave height, any increase in wave height requires a subsequent increase in energy required to create the wave, and an increase in wave making resistance. Thus, if wave height doubles, a four-fold increase in energy required to create the wave occurs. Therefore as ship speed increases and wave height increases, wave making resistance becomes dominant.

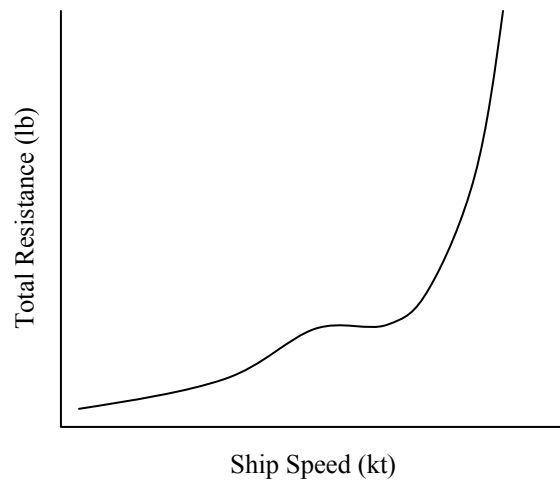


Figure 7.14 – Typical curve of total hull resistance

Experimental testing has shown that as the length of the bow wave approaches the length of the ship, the wave making component of resistance begins to increase rapidly. From wave theory the length of a free wave on the surface is related to velocity as follows:

$$L_w = \frac{2\pi V^2}{g}$$

where: L_w = wave length (ft)
 V = ship velocity (ft/s)

If ship length is substituted for wave length and the velocity term is corrected to ship speed in knots, the speed of the ship at which the length of the transverse bow wave is approximately that of the ship can be found using the following equation:

$$V_s = 1.34\sqrt{L_s}$$

where: V_s = ship speed (knots)
 L_s = ship length (ft)

The actual speed at which wave making resistance begins to increase rapidly will be somewhat less than the ship speed resulting from the above relationship.

Note: The sailing community refers to the speed obtained from the previous equation as the “hull speed”, a nominal maximum speed for a wind-propelled ship. This is nominal only, as there are many sailing hulls that exceed this speed. Hull speed has no meaning for a motor-driven ships because if enough power is used this speed can easily be exceeded.

So how does wave making resistance affect a ship and its operation? To illustrate, consider the following example:

The FFG-7 class ship has a waterline length of 408 ft and is powered by two gas turbine engines that produce approximately 41,000 SHP for a published maximum speed of 29 knots. At a speed of approximately 27 knots the length of the transverse wave is approximately the same length as the ship. With one gas turbine in operation (20,000 SHP), the ship is capable of speeds approaching 25 knots. It takes an additional 20,000 SHP (double the shaft horsepower) to increase speed by 4 knots! That increase in required horsepower is directly related to the effects of wave making resistance.

7.6.2.2 Reducing Wave Making Resistance

The question arises as how to reduce the effects of wave making resistance. In the design phase of a ship there are two things that can be done to reduce the effects of wave making, and therefore improve the performance of the ship:

- **Increasing length** of the ship increases the speed at which the length of the wave system generated by the ship is equal to ship length and therefore reduces the impact of wave making resistance.

As noted previously, the speed at which the wave length approaches ship length for an FFG-7 ($L_{pp} = 408$ ft, $\Delta = 4,000$ LT, rated at 41,000 SHP) is approximately 27 knots, whereas speed at which wave length approaches ship length for a NIMITZ-class carrier ($L = 1090$ ft, $\Delta = 97,000$ LT, approximately 280,000 SHP) is approximately 44 knots. At the FFG's top speed of 29 knots, the aircraft carrier is still in the relatively flat portion of the resistance/SHP curve. It would be very difficult to add enough propulsion machinery to the hull (space, weight, fuel, and center of gravity concerns) to increase the FFG-7's speed to an equivalent speed for the aircraft carrier. Therefore, longer ships use proportionally smaller engines to do the same speed as ships of less length. In other words, it requires fewer horsepower per ton to make the aircraft carrier (2.9 HP/LT) to achieve 30 knots than it does to make FFG-7 (10.3 HP/LT) achieve 29 knots. The relationship between length and resistance is best illustrated in Figure 7.15 on the following page. At a speed of 29 knots, the FFG-7 has a speed-length ratio of 1.4, giving the ship a large resistance coefficient. Compare the FFG to the aircraft carrier at 30 knots and a speed-length ratio of 0.90. The aircraft carrier has a much lower resistance coefficient and therefore requires significantly less horsepower per ton of displacement to achieve the same speed as the FFG.

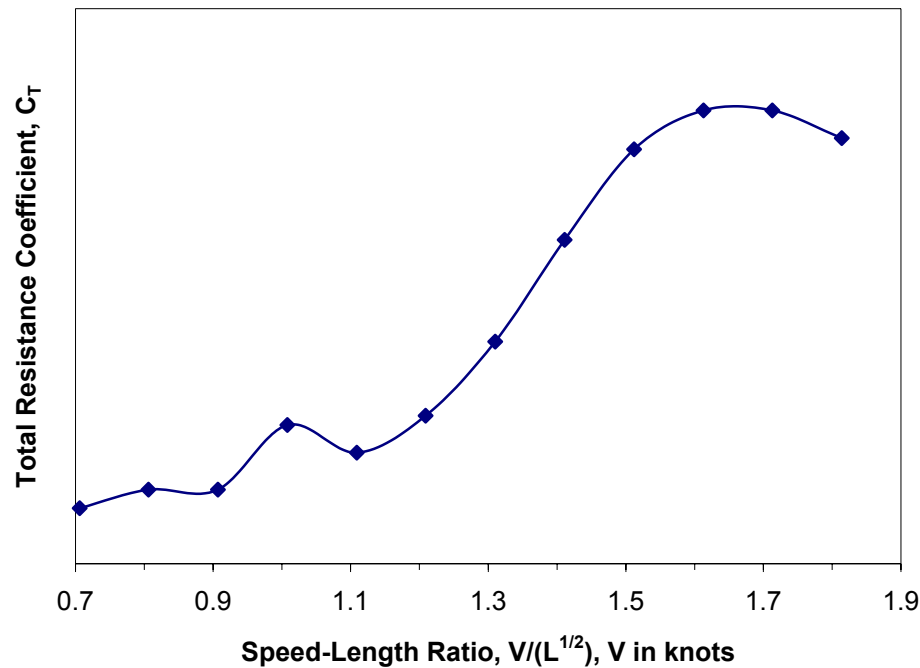


Figure 7.15 – Typical relationship between C_T and speed.

- Bulbous Bows.** Bulbous bows are one attempt to reduce the wave making resistance of surface ships by reducing the size of the bow wave system. The bulbous bow was developed by RADM David Taylor and was used as early as 1907 on the battleship *USS DELAWARE*. The “ram bows” of late 1800’s battle ships and even those of early Greek and Roman warships could also be considered early versions of the bulbous bow even though their bow designs were intended for other purposes. The idea behind a bulbous bow is to create a second bow wave that interferes destructively with the bow divergent wave, resulting in little to no wave at the bow. A smaller resultant bow wave improves the ship’s attitude in the water by producing less squat and trim by the stern. This more evenly trimmed ship results in less projected wetted surface area (i.e., less viscous resistance) and reduces the ship’s tendency to try to “climb” over its own bow wave as speed increases (i.e., delays the inception of large wave making resistance). A well-designed bulbous merchant ship bulb has been shown to reduce total resistance by up to 15%. This reduction in resistance translates into lower operating costs and higher profits for those merchant vessels that employ this design enhancement. Many warships also have bulbous bows. These bows often house the sonar transducers and keep them as far away as possible from the ship’s self-radiated noise. The bulbous bows of warships offer some reduction in wave making resistance and fuel savings. However, most warships cannot take full advantage of the bulbous bow since each bulb is generally “tuned” to the expected operating speed of the ship -- an easy task for a merchant which usually operates at a constant speed between ports, but not so simple for a warship whose operations necessitate frequent speed changes.

7.6.4 Air Resistance (R_{AA})

Air resistance is the resistance caused by the flow of air over the ship with no wind present. This component of resistance is affected by the shape of the ship above the waterline, the area of the ship exposed to the air, and the ship's speed through the water. Ships with low hulls and small sail area will naturally have less air resistance than ships with high hulls and large amounts of sail area. Resistance due to air is typically 4-8% of the total ship resistance, but may be as much as 10% in high sided ships such as aircraft carriers. Attempts have been made reduce air resistance by streamlining hulls and superstructures, however; the power benefits and fuel savings associated with constructing a streamlined ship tend to be overshadowed by construction costs.

7.6.5 Other Types of Resistance Not Included in Total Hull Resistance

In addition to viscous resistance, wave making resistance, and air resistance, there are several other types of resistance that will influence the total resistance experienced by the ship.

7.6.5.1 Appendage Resistance

Appendage resistance is the drag caused by all the underwater appendages such as the propeller, propeller shaft, struts, rudder, bilge keels, pit sword, and sea chests. In Naval ships appendages can account for approximately 2-14% of the total resistance. Appendages will primarily affect the viscous component of resistance as the added surface area of appendages increases the surface area of viscous friction.

7.6.5.2 Steering Resistance

Steering resistance is added resistance caused by the motion of the rudder. Every time the rudder is moved to change course, the movement of the rudder creates additional drag. Although steering resistance is generally a small component of total hull resistance in warships and merchant ships, unnecessary rudder movement can have a significant impact. Remember that resistance is directly related to the horsepower required to propel the ship. Additional horsepower is directly related to fuel consumed (more horsepower equals more fuel burned). A warship traveling at 15 knots and attempting to maintain a point station in a formation may burn up to 10% more fuel per day than a ship traveling independently at 15 knots.

7.6.5.3 Wind and Current Resistance

The environment surrounding a ship can have a significant impact on ship resistance. Wind and current are two of the biggest environmental factors affecting a ship. Wind resistance on a ship is a function of the ship's sail area, wind velocity and direction relative to the ship's direction of travel. For a ship steaming into a 20-knot wind, ship's resistance may be increased by up to 25-30%.

Ocean currents can also have a significant impact on a ship's resistance and the power required to maintain a desired speed. Steaming into a current will increase the power required to maintain speed. For instance, the Kuroshio Current (Black Current) runs from South to North off the coast of Japan and can reach a speed of 4-5 knots. What is the impact of this current? For a ship heading south in the current and desiring to travel at 15 knots it is not uncommon to have the propulsion plant producing shaft horsepower for speeds of 18-19 knots. Therefore, the prudent mariner will plan his or her voyage to avoid steaming against ocean currents whenever possible, and to steam with currents wherever possible.

7.6.5.4 Added Resistance Due to Waves

Added resistance due to waves refers to ocean waves caused by wind and storms, and is not to be confused with wave making resistance. Ocean waves cause the ship to expend energy by increasing the wetted surface area of the hull (added viscous resistance), and to expend additional energy by rolling, pitching, and heaving. This component of resistance can be very significant in high sea states.

7.6.5.5 Increased Resistance in Shallow Water

Increased resistance in shallow water (the Shallow Water Effect) is caused by several factors.

- The flow of water around the bottom of the hull is restricted in shallow water, therefore the water flowing under the hull speeds up. The faster moving water increases the viscous resistance on the hull.
- The faster moving water decreases the pressure under the hull, causing the ship to “squat”, increasing wetted surface area and increasing frictional resistance.
- The waves produced in shallow water tend to be larger than do waves produced in deep water at the same speed. Therefore, the energy required to produce these waves increases, (i.e. wave making resistance increases in shallow water). In fact, the characteristic hump in the total resistance curve will occur at a lower speed in shallow water.

The net result of traveling in shallow water is that it takes more horsepower (and fuel) to meet your required speed. Another more troublesome effect of high speed operation in shallow water is the increased possibility of running aground. One notable occurrence was in 1992 when the liner *QUEEN ELIZABETH II*, ran aground at a speed of 25 knots on a reef near Cuttyhunk Island in Massachusetts. The ship's nominal draft was 32 ft-4 inches and the charted depth of the reef was 39 feet. The 8.5-foot increase in draft was due to the shallow water effect known as *squat*.

Just as shallow water will adversely affect a ship's resistance, operating in a narrow waterway such as a canal can produce the same effect. Therefore when operating in a canal, the ship's resistance will increase due to the proximity of the canal walls and the decrease in pressure along the ships sides is likely to pull the ship towards the edge of the canal. The prudent mariner is advised to operate at moderate speeds when steaming in shallow and/or narrow waters.

7.6.6 Resistance and the Operator

There is a direct correlation between a ship's curve of total hull resistance, the EHP curve, the SHP curve, and the fuel consumption curve for a ship. What can the ship operator do to reduce the effects of viscous and wave making resistance?

- **Hull Cleaning.** The easiest method to reduce the effect of viscous resistance is to keep the hull clean and free of barnacles and underwater grasses. Section 7.6.2 indicated that frictional resistance is a function of surface roughness. Fouling of the hull can increase fuel consumption up to 15 percent. Keeping the underwater hull clean will reduce surface roughness and help minimize the effects of viscous resistance and conserve fuel. The Navy requires its ships to undergo periodic hull inspections and cleanings in order to reduce surface roughness. Ships are also periodically dry-docked and their bottoms are stripped and repainted to return the ships hull to a smooth condition.
- **Operate at a prudent speed.** To reduce the effects of wave making resistance, the operator should transit at speeds away from the humps in the resistance curve. From Figure 7.15 one such speed to avoid is when the speed-length ratio is approximately 1.0. For the FFG-7 this equates to a speed of approximately 20 knots. For best performance, operating at a speed-length ratio less than 0.9 is preferable. The standard transit speed for the US Navy is 14 knots, which puts most ships well below any point where the effects of wave making become a problem. For the FFG-7, a transit speed of 14 knots results in a speed-length ratio of approximately 0.7, well below the wave making threshold. At a speed of 14 knots, and aircraft carrier has a speed-length ratio of approximately 0.45, a speed where viscous resistance is the dominant component of resistance!

Traveling at high speeds corresponding to the humps in the C_T curve requires that the ship produce enough shaft horsepower to overcome the rapidly increasing wave making resistance. This rapidly increasing horsepower requirement means that fuel consumption will increase just as rapidly. For example, an FFG-7 with a clean hull traveling at 14 knots (speed-length ratio of 0.7) with one engine running will burn approximately 10,000 gallons of fuel per day. The same ship traveling at 29 knots (speed-length ratio of 1.4) with both engines in operation burns approximately 3,000 gallons of fuel **per hour**! Consider that the FFG-7 has a total fuel capacity of about 190,000 gallons, you can do the math and see why ships do not travel at high speeds for sustained periods.

Unlike warships whose maximum speed is determined by mission requirement, merchant ships are designed to travel at a speed corresponding to a hollow in the resistance curve. In fact, the service speed of a merchant ship is usually below the first hump speed. Most merchant ships have a service speed of approximately 15 knots, and if a length of 600 feet is assumed (speed-length ratio is 0.6), the ship is well below hump speed. Therefore less horsepower is required to propel the ship. Less horsepower equals smaller propulsion machinery, less fuel storage requirements, more cargo storage space, and therefore more chance to make money.

7.7 Determining the Total Hull Resistance and EHP Curves

Now that you have learned about the various components of ship resistance and how ship speed, resistance, and power are related; we now need to study how the EHP curve for a ship is obtained. One of the key phases in the design process for a ship is the determination of the amount of power required to propel a ship at either its maximum speed or service speed. This is necessary so the type and size of propulsion plant can be determined. Propulsion plant size is critical to the estimate of the location of the ship's center of gravity (stability concerns), and the amount of space to be set aside to accommodate the propulsion plant. Recall from section 7.3 that a ship's effective horsepower is related to total hull resistance by the following equation:

$$EHP = \frac{R_T V}{550 \frac{ft-lb}{sec-HP}}$$

Therefore, to determine effective horsepower for a given speed all the naval architect needs to do is to determine the total hull resistance at that speed. This presents a problem during design, as the ship only exists on paper and/or in the computer. There are two methods of predicting resistance and EHP curves for a ship during the design process: computer modeling and traditional tow tank testing with a model of the ship.

7.7.1 Computer Modeling

This method of determining a ship's resistance curve involves modeling the ship's hull in a computer and then solving three-dimensional fluid flow equations for the flow of water around the ship's hull. These equations are solved through a method called "computational fluid dynamics" using the finite element method of analysis. This method requires a large amount of computer memory and the ability to solve thousands of simultaneous equations. Computer modeling of the hull and the flow of water around the hull produces fairly accurate results (if you have a large enough computer) and can be used to compare many different hull designs.

Computer modeling does, however, have its drawbacks. Fluid flow around a ship's hull is very complex, especially near the stern where the hull's shape changes rapidly, and in many cases the flow in this region is difficult to analyze with the computer. This often necessitates the other method of determining a ship's resistance curve: tow tank testing of a model.

7.7.2 Theory Behind Ship Modeling and Tank Testing

Tow tank testing of a ship model is the traditional method of determining a ship's total hull resistance and its EHP curves. In this method, a model of the ship's hull is built and towed in a towing tank, measuring hull resistance at various speeds. The model results are then scaled up to predict full-scale hull resistance and EHP.

In order for model test results and full-scale ship predictions to be useable, two fundamental relationships between the model and ship must be met: geometric and dynamic similarity.

7.7.2.1 Geometric Similarity

Geometric similarity is obtained when all characteristic dimensions of the model are directly proportional to the ship's dimensions. The model is then a scaled version of the real ship – a very accurately scaled version of the ship. The ratio of the length of the ship to the length of the model is typically used to define the scaling factor (λ).

$$\text{Scale Factor} = \lambda = \frac{L_S(ft)}{L_M(ft)}$$

where: L_S = length of the ship
 L_M = length of the model

Note: the subscript “ S ” will be used to denote values for the full-scale ship and the subscript “ M ” will be used to denote values for the model.

From this it follows logically that the ratio of areas is equal to the scale factor squared and the ratio of volumes is equal to the cube of the scale factor. The characteristic area of importance for modeling is the wetted surface area of the underwater hull (S), and the characteristic volume of importance is the underwater volume of the ship (∇). These relationships are shown below:

$$\lambda^2 = \frac{S_S(ft^2)}{S_M(ft^2)} \qquad \lambda^3 = \frac{\nabla_S(ft^3)}{\nabla_M(ft^3)}$$

7.7.2.2 Dynamic Similarity

In addition to geometric similarity between model and full-scale ship, there must also be dynamic similarity between the model and its environment and the full-scale ship and its environment. Dynamic similarity means that the velocities, accelerations, and forces associated with fluid flow around both the model and full-scale ship have scaled magnitudes and identical directions at corresponding locations along the hull. The model must behave in exactly the same manner as the full-scale ship.

Unfortunately, it is physically impossible to achieve true dynamic similarity between the model and full-scale ship. Resistance is a function of velocity, water and air pressure, kinematic viscosity of water (ν), air and water density, and the acceleration due to gravity. It is impossible to scale gravity (think of a model having a scale ratio of 36 ... now, try to establish a lab environment whose acceleration of gravity is $1/36^{\text{th}}$ of 32.17 ft/sec^2). Similarly, it is impossible to scale water and its properties. Anyone who has seen Hollywood movies with ships at sea can appreciate this; the large globs of water “spray” coming from a model are not seen on a full-scale ship. Two fluids that come close to being scale versions of water are gasoline and liquid mercury; both of which pose serious health and safety issues.

So, if true dynamic similarity cannot be achieved, how can towing tanks exist, let alone produce meaningful results? The answer lies in achieving partial dynamic similarity between model and ship and Froude's "Law of Comparison", also referred to as the "Law of Corresponding Speeds".

7.7.2.3 The Law of Comparison and Tow Tank Testing

In previous sections of this chapter, we discussed ship resistance and ship performance in terms of dimensionless coefficients:

$$C_T = C_V + C_W$$

where: C_T = coefficient of total hull resistance

C_V = coefficient of viscous resistance

C_W = wave making coefficient

In an ideal world when comparing a geometrically similar ship and model, the coefficients of total resistance, viscous resistance, and wave making resistance would be equal. However, due to the viscous effects of water, this is not possible. The question is how to effectively take model data and calculate a coefficient of total hull resistance for the full-scale ship. This question was answered by Froude through his research on ship performance.

After many towing tank tests, Froude noticed that the wave pattern produced by a geometrically similar model and ship looked the same when the model and ship were traveling at the same speed to square root of length ratio. This is the Law of Corresponding Speeds, and is written as:

$$\frac{V_S}{\sqrt{L_S}} = \frac{V_M}{\sqrt{L_M}}$$

where: V_S = ship velocity (ft/s)

V_M = model velocity (ft/s)

L_S = ship length (ft)

L_M = model length (ft)

Because the wave patterns of the model and ship were similar using this relationship, Froude determined that it would be correct to use the same value of wave making coefficient (C_W) for both the model and ship when operating under these conditions, and therefore partial dynamic similarity between model and ship could be obtained. This can be summarized in the following mathematical relationships:

$$C_{WS} = C_{WM}$$

$$\text{if, } V_M = \frac{V_S \sqrt{L_M}}{\sqrt{L_S}} = \lambda^{-1/2} V_S$$

Example 7.4: A new type of destroyer is undergoing model testing in the tow tank. The ship has a length of 435 feet and the model has a length of 18 feet. The ship is to have a maximum speed of 35 knots. At what speed should the model be towed to achieve partial dynamic similarity for a speed of 35 knots?

Model speed is found using the law of corresponding speeds:

$$V_M = \frac{V_S \sqrt{L_M}}{\sqrt{L_S}}$$

$$V_S = (35 \text{ knots}) \times (1.688 \text{ (ft/sec)/kt}) = 59.08 \text{ ft/sec}$$

$$V_M = \frac{(59.08 \frac{\text{ft}}{\text{sec}})(\sqrt{18 \text{ ft}})}{\sqrt{435 \text{ ft}}} = 12.02 \frac{\text{ft}}{\text{sec}}$$

Therefore, partial dynamic similarity ($C_{WM} = C_{WS}$) is achieved for a speed of 35 knots if the model is towed at a speed of 12.02 ft/sec.

The purpose of towing tank testing is to tow the model at speeds that correspond to full-scale ship speeds, measure the model's resistance and determine the model's coefficient of wave making resistance. Knowing that the coefficient of wave making resistance of the model and full-scale ship are equal, one can easily determine the coefficient of total hull resistance for the ship. Once the full-scale resistance coefficient is known, the total hull resistance and EHP for the ship are calculated.

To summarize, resistance testing of a model in a towing tank utilizes the following generalized procedure:

- Determine the full-scale ship speed range for the test: minimum ship speed to a desired maximum speed.
- Determine towing speeds for the model using the Law of Comparison.
- Tow the model at each speed, recording the total hull resistance of the model.
- Determine the coefficient of total hull resistance for the model at each speed.
- Determine the coefficient of viscous resistance for the model at each speed.
- Calculate the wave making coefficient of the model at each speed
- $C_{WS} = C_{WM}$
- Determine the coefficient of viscous resistance for the ship at ship speeds corresponding to model towing speeds
- Determine the coefficient of total hull resistance for the ship at each speed.
- Determine the total hull resistance of the ship for each speed.
- Determine and plot the effective horsepower of the ship at each speed

Once the full-scale EHP curve is known, a similar shaft horsepower curve can be determined based on the assumed propulsive coefficient. The bottom line of EHP testing in the towing tank is to determine the amount of shaft horsepower that must be installed in the full scale ship in order to drive at its maximum speed. Once the maximum shaft horsepower is determined, the physical size and weight of the ship's propulsion plant can be resolved as well as the fuel storage requirements based on the expected steaming range (miles) of the ship. These factors are important in estimating the location of the ship's center of gravity as well as the design of the ship's structure.

7.8 The Screw Propeller

The screw propeller is the device most commonly used to transmit the power produced by the prime mover into the water and drives the ship. The theory behind the design of the screw propeller is very complicated and worthy of an entire course by itself. However, there are a few definitions, some basic theory, and propeller characteristics that should be known by all naval officers.

7.8.1 Screw Propeller Definitions

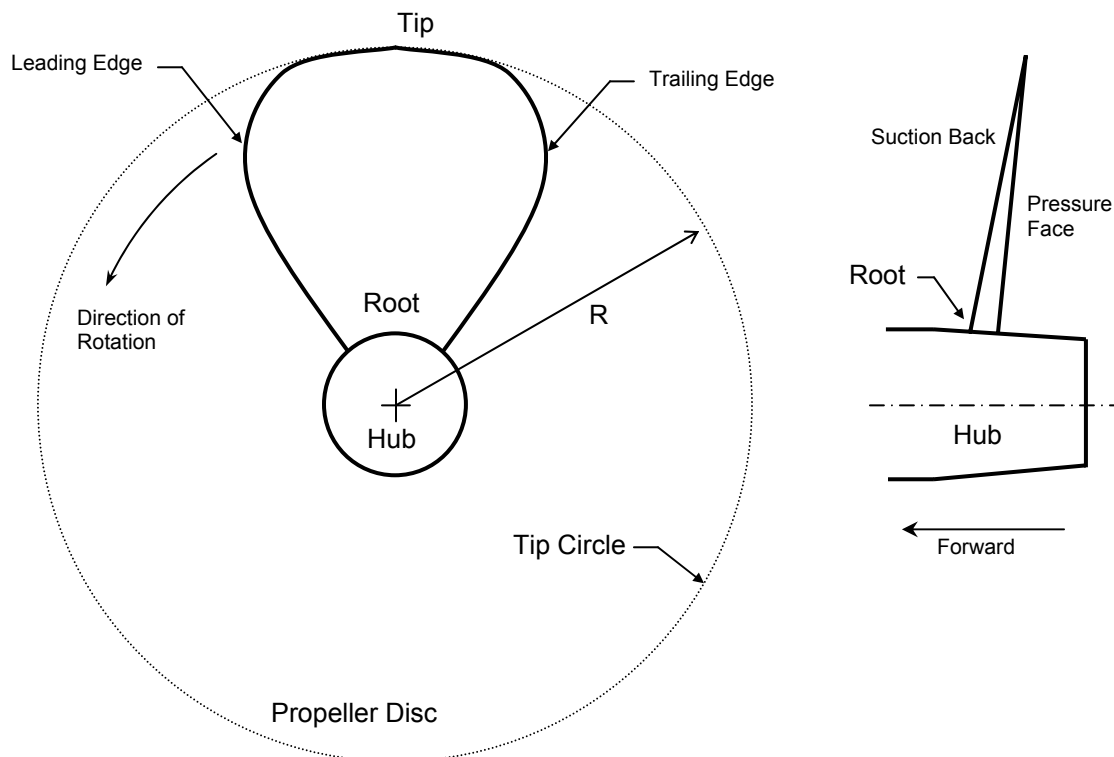


Figure 7.16 – Basic propeller geometry; left handed propeller viewed from astern.

- Propeller Radius (R) Distance from the propeller axis to the blade tip.
- Hub Connection between the blades and the propeller shaft
- Blade Tip Furthest point on the blade from the hub
- Blade Root Point where the blade joins the hub
- Tip Circle Circle described by the blade tips as the propeller rotates
- Propeller Disc Area described by the tip circle (propeller area, A_0)
- Leading Edge First portion of the blade to encounter the water
- Trailing Edge Last portion of the blade to encounter the water
- Pressure Face High pressure side of the propeller blade. Astern side of the blade when moving the ship forward
- Suction Back Low pressure side of the blade. Most of the pressure difference developed across the blade occurs on the low pressure side.

- Left Handed Screw Rotates counterclockwise when viewed from astern. Single screw naval vessels use this type of propeller.
- Right Handed Screw Rotates clockwise when viewed from astern. Twin screw naval vessels use one left handed and one right handed propeller.

7.8.2 Propeller Pitch (P)

Many times a propeller is referred to by its pitch. So, what is propeller pitch? Assuming the propeller shaft is rotating at a constant angular rate, and the ship is moving at a constant speed, as the propeller rotates and moves through the water, any point on the surface of a propeller blade will describe a helix in one 360° rotation of the shaft.

Propeller pitch (P) is the ideal linear distance parallel to the direction of motion that would be traveled in one revolution of the propeller shaft; similar to what happens when you turn a wood screw one revolution into a block of wood.

The pitch angle (ϕ) of a propeller is the angle that any portion of the blade makes from perpendicular to the water flow. Since any point on a propeller blade describes a helix, the pitch of a propeller (P) and pitch angle are related through the following equation:

$$\tan \phi = \frac{P}{2\pi r}$$

where: P = propeller pitch (ft)

ϕ = pitch angle (degrees)

r = radial distance of any point on the blade from the propeller shaft axis (ft)

This relationship is shown below in Figure 7.16.

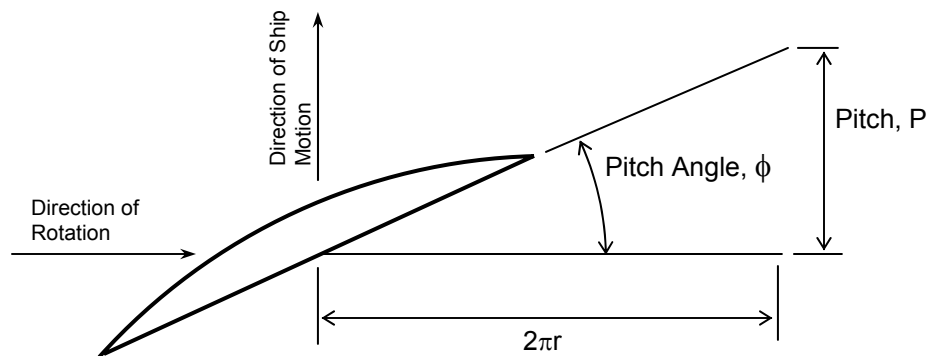


Figure 7.17 – Relationship between propeller pitch and pitch angle

There are various ways of describing a propeller with regards to its pitch:

Constant Pitch Propeller: The pitch (P) of the propeller is constant all the way from the blade root to the blade tip. Each point on the propeller blade will travel the same linear distance in one rotation of the propeller. When looking at a constant pitch propeller you will notice that the angle of the blades changes from root to tip. This is because the pitch (P) is constant and the relationship between pitch angle (ϕ) and pitch (P) is through the following equation:

$$\tan \phi = \frac{P}{2\pi r}$$

Consider a constant pitch propeller that is 14 feet in diameter with a pitch of 15 feet. The hub has a diameter of 5 feet. Using the above equation, one can easily determine the pitch angle at any point along the blade. For instance, at the root the blade has a pitch angle of 43.6° and at the tip the blade has a pitch angle of 18° . Constant pitch propellers are generally not used due to their inherent inefficiency.

A constant pitch propeller is illustrated below in Figure 7.17 (reproduced from “Introduction to Naval Architecture” by Gillmer and Johnson). Note how points ‘A’, ‘B’, and ‘C’ each travel the same distance in one revolution of the propeller.

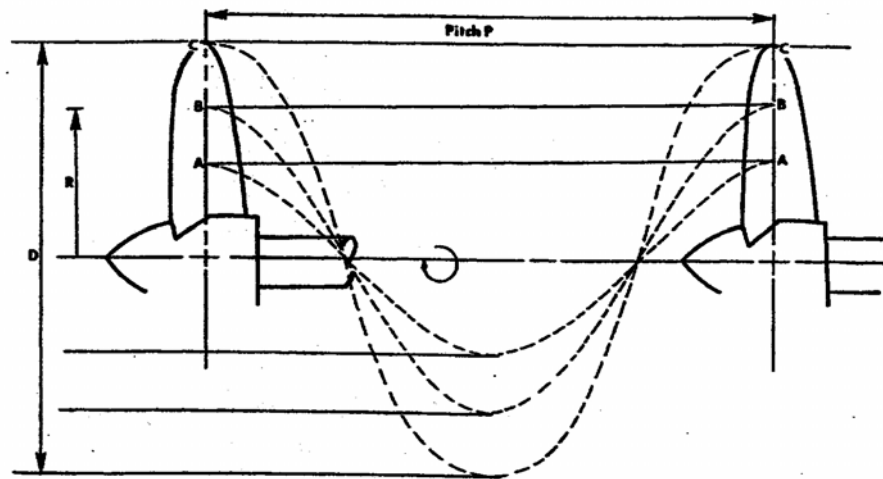


Figure 7.18 – Constant pitch propeller operating through one revolution.

Another type of constant pitch propeller is one in which the pitch angle (ϕ) is constant from blade root to tip. Although very inexpensive to produce, a propeller with constant pitch angle is rarely used.

Variable Pitch Propeller: The pitch (P) varies at each radial distance from the blade root to tip. Additionally, the pitch may vary across the face of the blade from leading edge to trailing edge at any radial distance from the hub. The nominal pitch value for a variable pitch propeller is taken at seventy percent of the blade radius ($0.7R$). A variable pitch propeller has distinct advantages

over a constant pitch propeller. A variable pitch propeller has greatly increased efficiency and is less likely to cavitate. Nearly every propeller in use today is a variable pitch propeller. Recall that increased propeller efficiency will increase a ship's propulsive efficiency (η_p), resulting in less shaft horsepower required to propel the ship at a given speed.

Fixed Pitch Propeller: A fixed pitch propeller is a propeller whose blade is fixed with respect to the hub and cannot be changed while the propeller shaft is rotating. A fixed pitch propeller may have either constant or variable pitch blade shape. Most propellers in service today, from those attached to outboard engines or to the large screws of aircraft carriers, are fixed variable pitch propellers.

Controllable Pitch Propeller: This type of propeller design allows the position of the propeller blade with respect to the hub to be changed while the propeller shaft is rotating. This is accomplished by using an electro-hydraulic system to change the pitch angle of the blades. While the entire propeller is classified as a controllable pitch propeller, the blades can also be variable pitch, producing a controllable variable pitch propeller. A controllable pitch propeller can significantly improve the control and ship handling capabilities of a ship. It also obviates the need for a prime mover reversing mechanism because the pitch angle can be changed such that the blades provide reverse thrust without changing the direction of shaft rotation. This type of propeller is found on FFG 7, DD 963, DDG 51, CG 47, and LSD 51 classes of ship.

7.8.3 How a Propeller Blade Works

A propeller blade works in the same manner as an aircraft wing. Water flow over the propeller blade creates a pressure differential across the blade which creates a lifting or thrust force that propels the ship through the water. If we were to make a cut through a propeller blade, we would see that the blade has a shape similar to an aircraft wing. Figure 7.18 illustrates this concept. Water velocity over the suction back of the blade is greater than the velocity across the high-pressure face of the blade. Using Bernoulli's equation (from Chapter 1), this velocity differential across the blade results in a pressure differential across the blade. The resultant lifting force can be resolved into thrust and resistance vectors. It is the thrust vector that pushes the ship through the water.

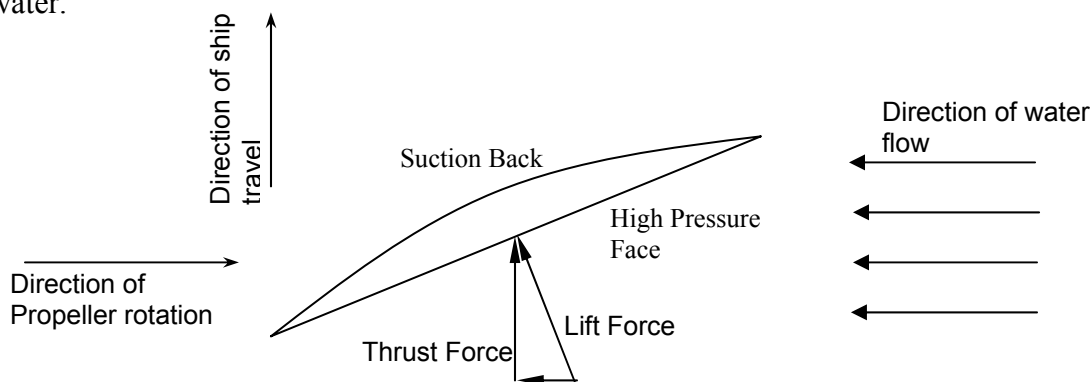


Figure 7.19 – Forces acting on a propeller blade

7.8.4 Momentum Theory of Propeller Action (OPTIONAL)

There are several theories on fluid dynamics used to describe the operation of a screw propeller. These include momentum theory, impulse theory, blade element theory, and circulation theory. Each of these theories is used by naval architects to design a propeller and analyze its performance. The momentum theory is presented here because it gives some valuable insight into the operation of a propeller without the burden of advanced mathematics.

7.8.4.1 Speed of Advance (V_A)

Before a study of momentum theory can proceed, it is necessary to understand the concept of the speed of advance (V_A) of a propeller. As a ship moves through the water at some velocity (V_S), it drags the surrounding water with it as explained earlier in the section on viscous resistance. At the stern of the ship, this causes the wake to follow along with the ship at a wake speed (V_W). Consequently the propeller is experiencing a flow velocity less than the ship's velocity. The flow velocity through the propeller is called the speed of advance (V_A). Figure 7.19 illustrates this concept.

$$V_A = V_S - V_W$$

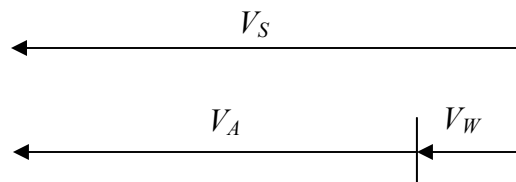


Figure 7.20 – Speed of advance

7.8.4.1 Momentum Theory

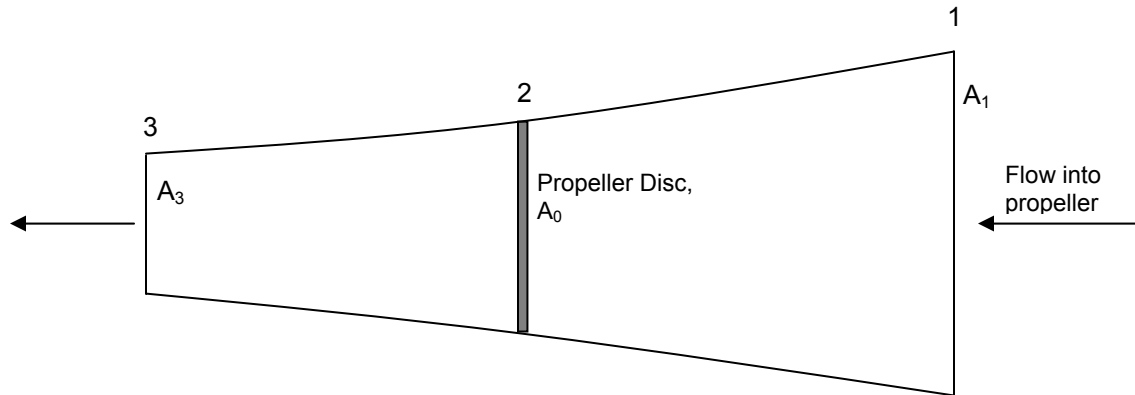
The momentum theory is used to describe the action of an “ideal” propeller. In this theory, the exact nature of the propeller (pitch, number of blades, shaft rpm, etc) is not important. The propeller itself is assumed to be a “disc” of area A_0 (disc area). The propeller causes an abrupt increase in pressure as the fluid passes through the disc coupled with an increase in fluid velocity. The method by which this occurs is ignored.

Momentum theory makes the following assumptions regarding the propeller and the flow through the propeller:

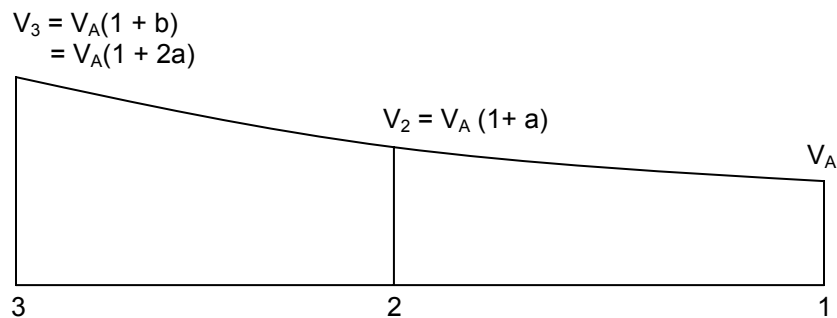
1. The propeller imparts a uniform acceleration to the water passing through it and the thrust generated by the propeller is uniformly distributed over the entire disc.
2. The flow is frictionless.
3. There is an unlimited supply of water available to the propeller.

Let's look at the propeller and a control volume of water around the propeller. The control volume extends to some station 1 ahead of the propeller to some station 3 astern of the propeller as shown below. Station 2 represents the propeller disc area (A_0). Since the assumption is made that the propeller imparts a uniform acceleration to the water, this implies that the cross section area of the control volume must decrease from station 1 to station 3.

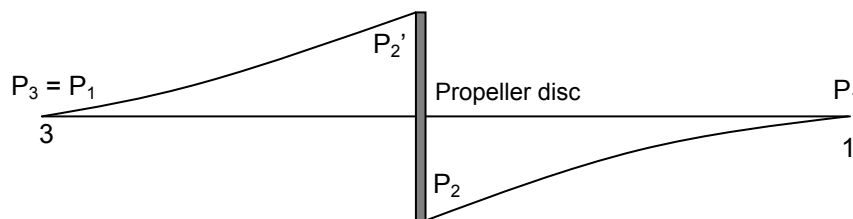
- Cross section area of the flow decreases through the propeller.



- Flow velocity increases from the speed of advance (V_A) at point 1 to velocity V_3 as cross section area of the flow decreases from station 1 to station 3. The “ a ” and “ b ” terms are an axial-inflow factor and will be discussed later.



- Pressure decreases as fluid velocity increases through the propeller. Note that the propeller causes an increase in pressure between the suction back (P_2) and pressure face (P_2'). Note that at some distance ahead and astern of the propeller, pressures are equal.



7.8.4.2 Determination of Propeller Thrust (OPTIONAL)

Momentum theory states that the thrust produced by a propeller is equal to the change in momentum of the fluid per unit time as it passes through the control volume from station 1 to station 3.

The volume flow rate of water through the propeller disc is:

$$Q = V_A(1 + a)A_0$$

Neglecting any effect of rotation that may be imparted to the flow by the propeller disc, the change in momentum per unit time between stations 1 and 3 is:

$$\begin{aligned} & \rho Q(V_3 - V_A) \\ &= \rho Q[V_A(1 + b) - V_A] \end{aligned}$$

Therefore, the thrust produced by the propeller is:

$$T = \rho Q[V_A(1 + b) - V_A] = \rho Q V_A b$$

Therefore, propeller thrust is a function of the mass flow rate of water through the propeller and the change in fluid velocity through the propeller. Thrust can be increased by either increasing the flow rate through the propeller disc or by increasing the velocity differential between stations 1 and 3.

Substituting the above expression for flow rate through the disc produces the following expression for propeller thrust:

$$T = \rho A_0 V_A^2 (1 + a) b$$

The terms “ a ” and “ b ” are axial-inflow factors and are used to describe the increase in fluid velocity through the propeller from station 1 to station 3. It can be shown that axial inflow factors “ a ” and “ b ” are related by the following expression:

$$b = 2a \quad \text{or} \quad a = b/2$$

The significance of this relation is that one half of the increase in fluid velocity through the propeller is obtained prior to the fluid reaching the propeller disc. In other words, the decrease in pressure at the suction back of the propeller causes fluid velocity to increase. Substituting $a = b/2$ into the equation for thrust produces the following expression for propeller thrust:

$$T = \rho A_0 V_A^2 b(1 + b/2)$$

Rearranging this expression produces the following:

$$T = \frac{1}{2} \rho A_0 V_A^2 (2b + b^2)$$

We will use the above relationship for propeller thrust to describe thrust loading on the propeller and the efficiency of the propeller.

7.8.4.3 Thrust Loading Coefficient (C_T) (NOT OPTIONAL)

The coefficient of thrust loading (C_T) is the dimensionless form of thrust and is defined by the following equation:

$$C_T = \frac{T}{\frac{1}{2} \rho A_0 V_A^2}$$

Comparing this equation to the above relation for thrust reveals that:

$$C_T = 2b + b^2$$

7.8.4.4 Ideal Propeller Efficiency (η_I) (NOT OPTIONAL)

The ideal efficiency of a propeller is the ratio of useful work obtained from the propeller and work expended by the propeller on the water. The work done on the water by the propeller thrust is $TV_A(1 + a)$, and the work obtained from the propeller is TV_A . The ideal propeller efficiency is:

$$\eta_I = \frac{TV_A}{TV_A(1 + a)}$$

However, $a = b/2$, and substituting this expression into the equation for ideal efficiency produces:

$$\eta_I = \frac{TV_A}{TV_A(1 + a)} = \frac{1}{1 + a} = \frac{1}{1 + b/2} = \frac{2}{2 + b} = \frac{2}{1 + (1 + b)}$$

Rearranging the expression for C_T produces the following expression for C_T and b :

$$\sqrt{1 + C_T} = (1 + b)$$

Substituting into the above expression for ideal propeller efficiency produces:

$$\eta_I = \frac{2}{1 + \sqrt{1 + C_T}}$$

7.8.4.5 Propeller Characteristics

Momentum theory gives us the following relationships:

$$\eta_I = \frac{2}{1 + \sqrt{1 + C_T}} \quad \text{where} \quad C_T = \frac{T}{\frac{1}{2} \rho A_0 V_A^2}$$

From these two relationships we can look at how different factors affect the performance of a propeller. For a given thrust (T) and speed of advance (V_A), the thrust loading coefficient will decrease as the propeller disc area (A_0) increases. A decrease in propeller thrust loading results in an increase in the ideal propeller efficiency.

Since thrust and fluid velocity through the propeller vary with ship speed, one of the principle deciding factors in propeller design is the size of the propeller. Larger propellers reduce thrust loading and improve efficiency. Increased propeller efficiency increases the propulsive coefficient and reduces the amount of shaft horsepower required to achieve desired ship speed through the water. Decreasing the amount of horsepower required reduces the size (and cost) of propulsion machinery and reduces the amount of fuel required. Merchant ships have hulls designed to use a single large propeller in order to achieve increased propeller efficiency. Naval vessels, because of hull form constraints and the need for quick acceleration, tend to use smaller propellers. This does not imply that naval propellers are less efficient than merchant propellers; there are many other aspects of propeller design that help improve propeller efficiency.

The equation for ideal propeller efficiency given above should not be confused with actual propeller efficiency discussed in section 7.2.4. The ideal propeller efficiency is based on frictionless, irrotational flow through the propeller. Because of friction, rotational factors, and other losses, the actual efficiency of a propeller is approximately 20% less than the ideal efficiency given above. However, the idea of increasing the size of the propeller to improve efficiency is still valid.

What happens if the ship is not moving? Many of you by now have thought about what happens to efficiency when V_A is zero (i.e. the ship is not moving). The previous equations imply that when ship speed is zero there should be infinite thrust loading and zero propeller efficiency. This is not the case. In fact, as soon as the propeller shaft starts to rotate, the propeller will begin accelerating fluid through the propeller and develop thrust. This is what enables tugboats to operate at low speed and generate large amounts of thrust. Tugboats have very large propellers that are designed to accelerate water through the propeller disc at low speed of advance and produce large amounts of thrust. The zero speed of advance condition for a tugboat is called the “*bollard pull*” condition and all tugs have a bollard pull rating in long tons. Bollard pull is the force exerted by the ship at zero speed.

Ships equipped with gas turbine engines and controllable pitch propellers have also discovered that propellers produce thrust at zero speed the hard way. When starting the turbines, propeller pitch is to be set at zero thrust because the propeller shaft begins to rotate as soon as the turbines

are started. On several occasions the engines have been started without propeller pitch set at zero thrust and the ship commenced moving, much to the chagrin of all.

How do propeller pitch and the number of blades affect propeller performance?

Momentum theory does not address such matters as the pitch of a propeller, the number of blades in the propeller, or even propeller shaft rotation (rpm). Momentum theory is only concerned with the change in momentum of fluid passing through the propeller. As you might expect, pitch, number of blades, and shaft rpm do affect the performance of a propeller. One common equation used in propeller design is a different dimensionless coefficient of propeller thrust:

$$K_T = \frac{T}{\rho n^2 D^4}$$

where: K_T = thrust coefficient

ρ = water density

n = propeller shaft rpm

D = propeller diameter

Note again that the number of blades is not a factor in propeller performance, but overall propeller size is the driving factor. Performance is not a function of the number of blades but the blade area and propeller diameter; more blade area in contact with the water produces more thrust. Modern propellers have blades whose total area occupies the entire propeller disc area. The pitch of a propeller is engineered to meet the thrust requirements. In general, a propeller is designed to meet the needs of a specific ship or class of ship. Therefore, all propellers are different according to their specific application.

For further information on propellers and propeller theory, read Volume 2 of “Principles of Naval Architecture”, published by the Society of Naval Architects and Marine Engineers.

7.8.5 Propeller Cavitation

Cavitation is the formation and subsequent collapse of vapor bubbles in regions on propeller blades where pressure has fallen below the vapor pressure of water. Cavitation occurs on propellers that are heavily loaded, or are experiencing a high thrust loading coefficient.

7.8.5.1 Types of Cavitation

There are three main types of propeller cavitation:

- **Tip** Blade tip cavitation is the most common form of cavitation. Tip cavitation forms because the blade tips are moving the fastest and therefore experience the greatest dynamic pressure drop.

- **Sheet** Sheet cavitation refers to a large and stable region of cavitation on a propeller, not necessarily covering the entire face of a blade. The suction face of the propeller is susceptible to sheet cavitation because of the low pressures there. Additionally, if the angle of attack of the blade is set incorrectly (on a controllable pitch propeller, for instance) it is possible to cause sheet cavitation on the pressure face.
- **Spot** Spot cavitation occurs at sites on the blade where there is a scratch or some other surface imperfection.

7.8.5.2 Consequences of Cavitation

The consequences of propeller cavitation are not good and can include the following:

- Reduction in the thrust produced by the propeller.
- Erosion of the propeller blades. As cavitation bubbles form and collapse on the tip and face of a propeller blade, pressure wave formed causes a small amount of metal to be eroded away. Excessive cavitation can erode blade tips and cause other imperfections on the blade's surface.
- Vibration in the propeller shafting.
- Increase in ship's radiated noise signature.

In the case of a warship, cavitation is to be avoided because the noise of cavitation can compromise the location of the vessel. This is especially important when operating in the vicinity of enemy submarines. The Prairie-Masker system, used on several different classes of warship (FFG-7, DD-963, DDG-51, and CG-47 for instance) is highly effective at reducing machinery and cavitation noise. The Prairie portion of the system routes compressed air from the turbines to the leading edges and propeller blade tips (the most likely location for cavitation to form), where it is released into the water through small holes. The air bubbles released from the propeller helps reduce cavitation and dampen the effect of collapsing vapor bubbles caused by cavitation.

7.8.5.3 Preventing Cavitation

Several actions can be taken to reduce the likelihood of cavitation occurring:

- **Fouling** The propeller must be kept unfouled by marine organisms and free of nicks and scratches. Fouling causes a reduction in propeller efficiency as well as the increased chance for cavitation. Even a small scratch can cause significant spot cavitation and result in an increase in radiated noise as well as erosion of the blades. The Navy conducts regular underwater inspections and cleaning of its propellers to prevent the effects of fouling.
- **Speed** Every ship has a cavitation inception speed, a speed where tip cavitation begins to form. Unless operationally necessary, ships should be operated at speeds below cavitation inception.

- **Thrust** For ships with manual throttles (steam turbine), the Throttleman must not increase shaft speed and thrust too quickly when accelerating the ship. An analysis of the equation for the thrust coefficient (C_T) reveals that high propeller thrust (T) and low speed through the propeller (V_A) increases the thrust loading coefficient which may result in cavitation.

$$C_T = \frac{T}{\frac{1}{2} \rho A_0 V_A^2}$$

When accelerating the ship, the Throttleman should open the throttle slowly, allowing flow velocity to increase or decrease proportionally with propeller thrust. Ships may use an acceleration table to guide the Throttleman in opening throttles or hydrophones calibrated to detect cavitation from the propeller.

- **Pitch** Operators of ships with controllable pitch propellers must take care that propeller pitch is increased or decreased in a smooth manner. This is usually done as part of the ship's propulsion control system. Incorrect operation of the pitch control system may cause high thrust loading on the propeller blades and increase the likelihood of cavitation.
- **Depth** Since cavitation is a function of hydrostatic pressure, increasing hydrostatic pressure (i.e. depth) will reduce the likelihood of cavitation. Submarines are uniquely susceptible to depth effects and cavitation as the depth of the submarine affects hydrostatic pressure at the propeller blades. When operating at shallow depth, hydrostatic pressure is decreased and the propeller cavitates at lower shaft rpm and low thrust loading. As a submarine's depth increases, hydrostatic pressure increases and cavitation inception is delayed. Therefore, a submarine can operate at higher speeds at deeper depths with little worry about cavitation noise.

7.8.5.4 Propeller Ventilation

Ventilation is a propeller effect often confused with cavitation. If a propeller operates too close to the surface of the water, the localized low pressure created by the propeller blades can draw air under the water and cause effects similar to those mentioned for cavitation.

Ventilation is most likely to occur when operating in a very light displacement condition (a condition common to merchant ships transiting in ballast), ships operating in rough seas where ship motion causes the propeller to go in and out of the water, and in ships with a large negative trim (trim down by the bow).

CHAPTER 7 HOMEWORK

Section 7.2

1.
 - a. Draw a simplified picture of a ship's drive train with a prime mover, reduction gear, bearings, shaft seal, strut, and propeller.
 - b. Show where Brake Horsepower, Shaft Horsepower, Delivered Horsepower, and Thrust Horsepower would be measured.
 - c. Rank the powers in 1(b) from highest to lowest in magnitude.
2. A ship with a drive train illustrated in Figure 7.1 has the following mechanical efficiencies:

| | |
|---------------------|------------------------------|
| Reduction Gear | $\eta_{\text{gear}} = 95\%$ |
| Bearings/Seal/Strut | $\eta_{\text{shaft}} = 98\%$ |

Calculate the power delivered to the propeller if the prime mover is producing 10,000 brake horsepower.

Section 7.3

3.
 - a. What is Effective Horsepower?
 - b. How is EHP determined in the design of a ship?
 - c. Why is the determination of EHP critical in the design of a ship?

Section 7.4 – 7.5

4. Towing tank testing has predicted that a ship will have an EHP of 33,000 HP when traveling at a speed of 25 knots. What will be the required SHP if the ship has a propulsive efficiency of 60%?
5. Towing tank testing has predicted that a ship will have an EHP of 50,000 HP when traveling at a speed of 30 knots. Determine the SHP required to propel the ship at 30 knots for each of the following propulsive efficiencies:
 - a. 55%
 - b. 60%
 - c. 65%

6. A twin-screw ship has the following EHP data:

| Ship Speed | EHP |
|-------------------|-------------|
| (knots) | (HP) |
| 0 | 1 |
| 6 | 50 |
| 10 | 110 |
| 11 | 180 |
| 12 | 250 |
| 13 | 360 |
| 14 | 520 |
| 15 | 820 |

- Plot the EHP curve for this ship. Ensure you make the plot large enough to be useful; you will need data from this plot for the remainder of the problem.
 - Assuming a propulsive efficiency of 55%, determine the top speed of the ship when it is operating both engines producing 700 SHP each.
 - Assuming the same propulsive efficiency, determine the ship's speed when operating one engine producing 700 SHP.
7. A ship has hull resistance data shown in the table below.

| Ship Speed | Total Hull Resistance |
|-------------------|------------------------------|
| (knots) | (lbs) |
| 5 | 70,000 |
| 10 | 100,000 |
| 13 | 135,000 |
| 15 | 170,000 |
| 17 | 220,000 |
| 20 | 265,000 |
| 23 | 375,000 |
| 25 | 500,000 |

- Plot the resistance data and determine the effective horsepower required for a speed of 22 knots.
- If the ship has a propulsive efficiency of 60%, what shaft horsepower is required to achieve a speed of 22 knots?
- The ship is to have a maximum speed of 25 knots. How many shaft horsepower must be installed to achieve this speed?

8. What would happen to the total hull resistance if the ship's draft (i.e. displacement) were to increase?

Section 7.6

Components of Total Hull Resistance

9. a. Name the components of total hull resistance in calm water.
- b. Which component dominates at slow speeds?
- c. Which component dominates at high speeds?

Viscous Resistance

10. a. Define laminar and turbulent flow.
- b. A ship with $L_{pp} = 500$ feet is traveling at a speed of 25 knots. Calculate the Reynolds number for this ship and speed. Also determine the nominal length of laminar flow along the hull at this speed.
- c. The same ship has slowed to a speed of 5 knots. Determine the new Reynolds number for the ship. Determine the nominal length of laminar flow along the hull associated with this speed.
11. Draw a waterplane view of a moving ship showing laminar flow at the bow, the transition point, boundary layer, flow separation, and wake.
12. How does an increase in ships speed affect viscous resistance?
13. A DDG ($L_{pp} = 465$ ft) and an AOE ($L_{pp} = 740$ ft) are steaming together at a speed of 23 knots. Which ship will have a greater skin friction coefficient (C_F)?
14. An FFG ($\Delta = 4000$ LT, $L_{pp} = 408$ ft, and $T = 16$ ft) and a CVN ($\Delta = 88,000$ LT, $L_{pp} = 1080$ ft, $T = 37$ ft) are steaming at the same Reynolds number. Which ship will have the greater coefficient of viscous resistance? Explain your answer.

Wave Making Resistance

15. Briefly describe the two major wave systems produced by a ship moving through calm water. Use a sketch to aid your description.
16. Why are there humps and hollows in the curve of total hull resistance? Sketch and label this curve.

17. How can the ship operator reduce the effects of wave making resistance?

Other Types of Resistance

18. Name and describe four other types of resistance not included in the total hull resistance.
19. Why does it take more power to achieve the same speed in shallow water than in deep water? What dangers are associated with operating at high speed in shallow water?
20. How can the operator take advantage of environmental factors to reduce resistance?

Section 7.7

21. Briefly explain the terms geometric similarity and dynamic similarity.
22. Explain how geometric similarity and partial dynamic similarity are achieved in resistance testing.
23. A new class of supply ship is being tested in the towing tank. The ship has a length of 680 ft and the model is built to a scale factor of 29.57.
- a. What length is the model?
 - b. The ship has a maximum speed of 20 knots. What speed must the model be towed at in order to achieve partial dynamic similarity?
 - c. What is the purpose of towing tank testing?

Section 7.8

Propellers

24. On a sketch of a screw propeller, show the hub, blade tip, blade root, propeller diameter, pressure face, and suction back.
25. Describe two methods for quantifying the pitch of a propeller.
26. Briefly describe the differences between fixed pitch, variable pitch, and controllable pitch propellers.
27. A propeller is described as having a pitch of 15 feet. What does this mean for the ship's operator?

Thrust Loading Coefficient

28. Using the equations for the thrust loading coefficient and ideal propeller efficiency, answer the following:
- a. Will a larger propeller be more or less efficient than a smaller propeller?
 - b. Will high thrust and low ship speed give high or low efficiency?

Cavitation

29. Briefly describe why propeller cavitation occurs.
30. What is the relationship between thrust loading and propeller cavitation?
31. Explain the following terms:
- a. Tip cavitation
 - b. Sheet cavitation
 - c. Spot cavitation
32. What measures can the operator take to minimize propeller cavitation?